Axion Searches with High Power Lasers and XFELS

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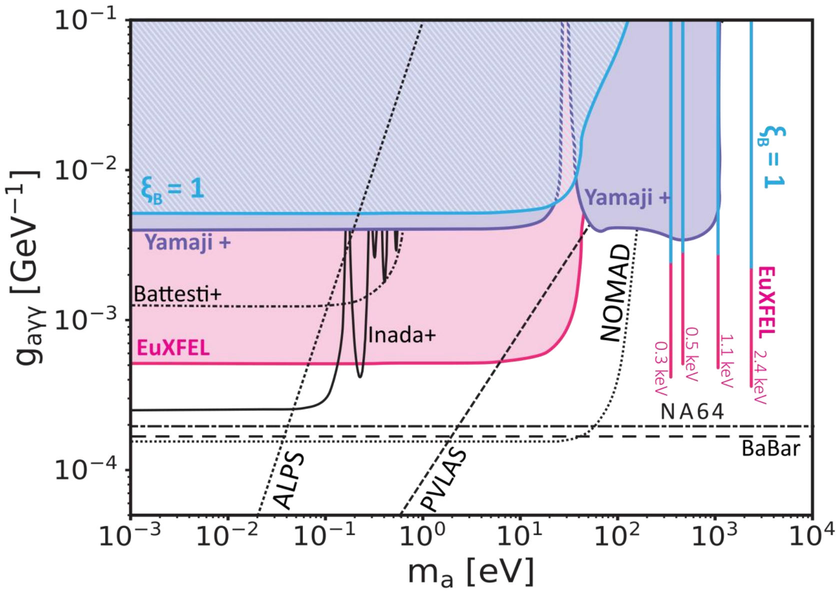
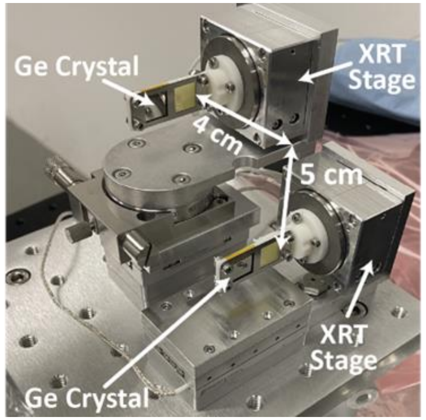
Axion searches: AAC2026 July 2026

Overview

- Introduction to Axions / ALPS and overview of search strategies
- Experimental design for a light shining through a wall experiment with an X-Ray Free Electron Laser (XFEL)
- Experimental data for initial experiments using high power laser
- Coupling axions and lasers, parametric instabilities.
- Fundamental physics with high powered lasers

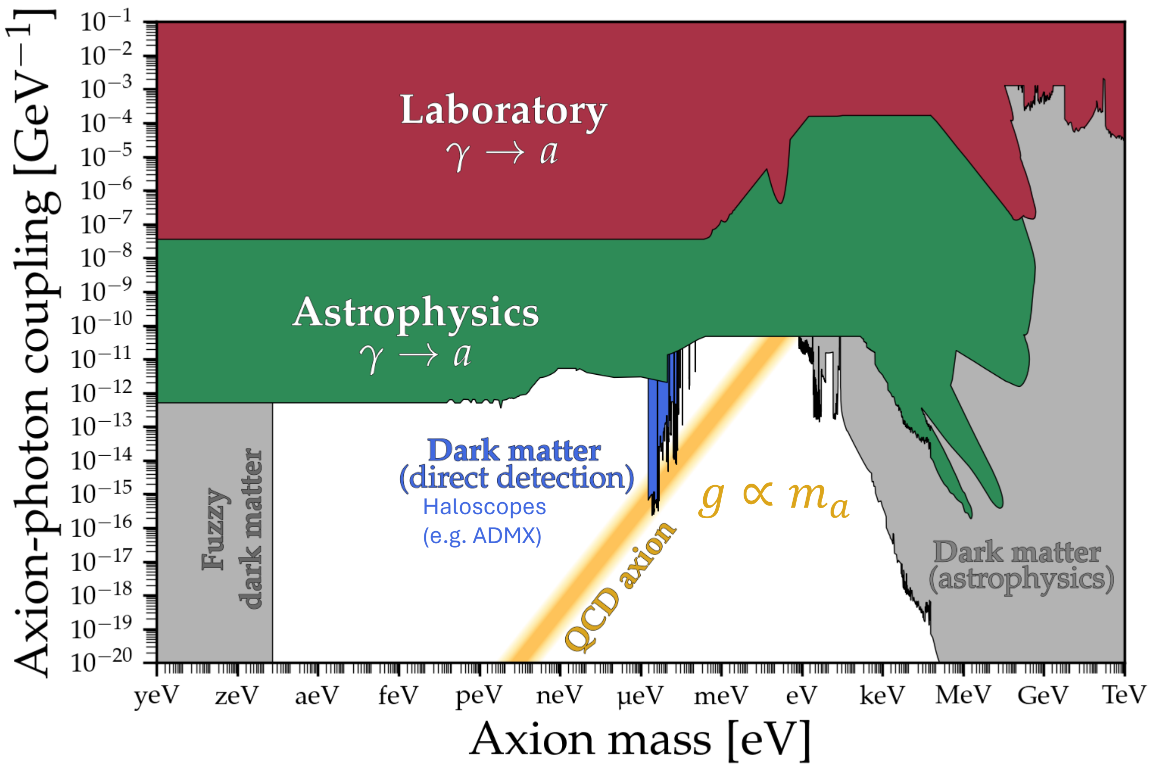




Axions solve the strong CP problem and are a cold dark matter candidate

- Postulated to explain the *absence* of CP-violation in strong interactions (which would otherwise generate an electric dipole moment for the neutron)
- The axion arises from spontaneous breaking of the Peccei-Quinn (PQ) symmetry
- Axion-like particles (ALPs) also arise generically in string theory
- Light axions ($m_a \sim 10^{-6} - 10^{-2}$ eV) are a natural candidate for cold dark matter
- Laboratory searches target this light axion window

F. Chadha-Day *et al.* “*Axion dark matter: What is it and why now?*” *Sci. Adv.* **8**, eabj3618 (2022).



Credit: Ciaran O'Hare (github.com/cajohare/AxionLimits)

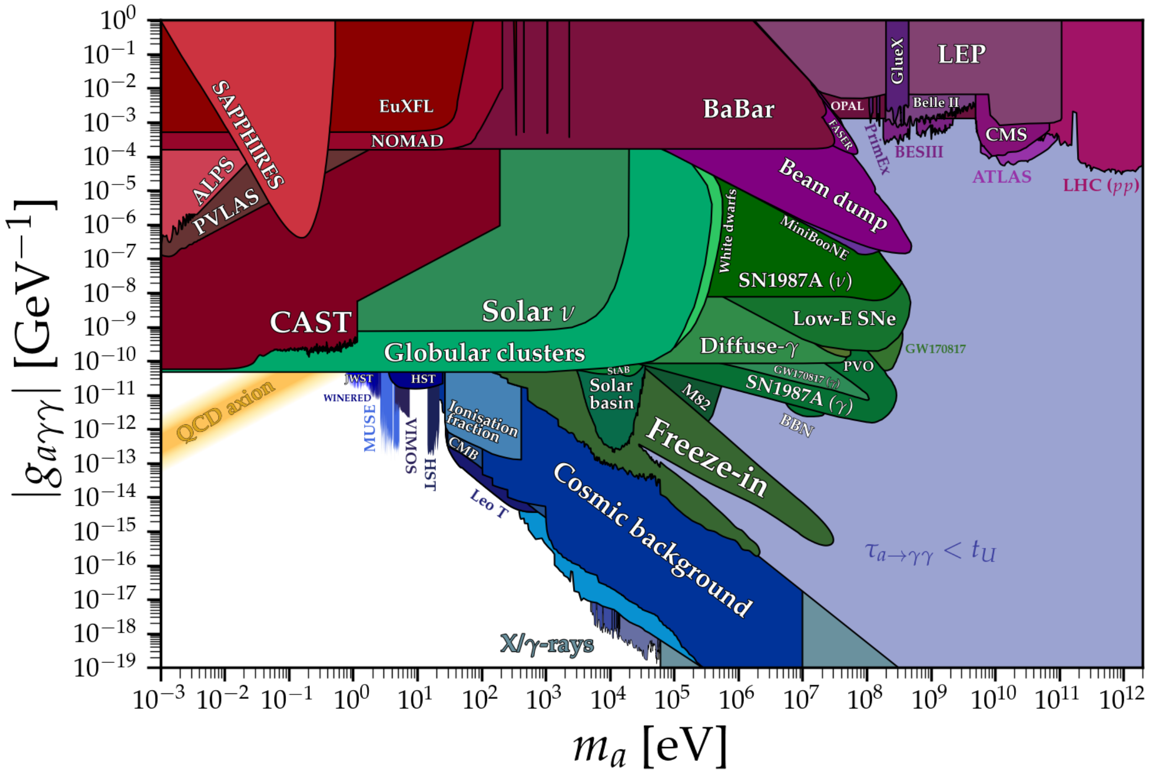
There has recently been interest in heavier axions, which motivates our study

- Recent suggestion: When PQ symmetry is broken *after* cosmological inflation, axions are also produced in the decay of axion domain walls

- Taking this additional contribution into account requires axions which make up dark matter to have a **mass above 10^{-2} eV**

A. Ringwald & K. Saikawa, "*Axion dark matter in the post-inflationary Peccei-Quinn symmetry breaking scenario*". Phys. Rev. D **93**, 085031 (2016).

K. Beyer & S. Sarkar, "*Ruling out light axions: The writing is on the wall*", SciPost Phys. **15**, 003 (2023).



Credit: Ciaran O'Hare (github.com/cajohare/AxionLimits)

There are a variety of complimentary axion search strategies

Increased sensitivity

Astrophysical

Axion losses in stellar models

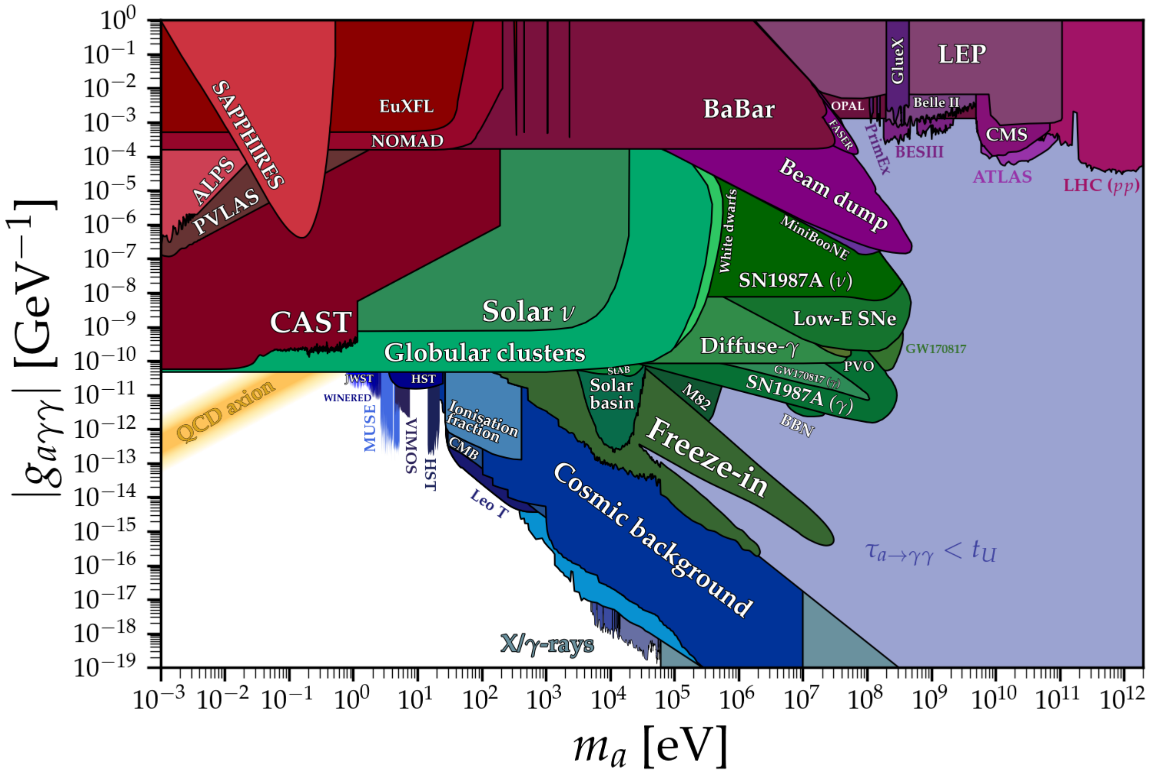
Lab detection

Helio/haloscopes

Lab generation

Generate (& detect) terrestrially

Reduced model dependence



Credit: Ciaran O'Hare (github.com/cajohare/AxionLimits)

Yannis K. Semertzidis & SungWoo Youn, "*Axion dark matter: How to see it?*", Sci. Adv. **8**, eabm9928 (2022).

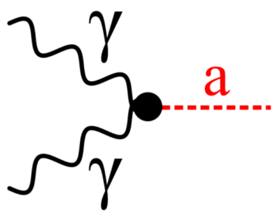
A. Caputo & G. Raffelt, *"Astrophysical Axion Bounds: The 2024 Edition",* Proceedings of Science **454**, 041 (2024).

Photon-Axion Coupling

Photon axion interaction:
Mode conversion equations describing coupling: Axions, Neutrinos, Photons

Axions convert into photons via the Primakoff effect:

$$\mathcal{L}_{\text{axion}} = g_{a\gamma\gamma}\boldsymbol{E}\cdot\boldsymbol{B}a$$



- Equations describing photon magnetic field axion coupling.

The equations for axions coupling to photons,

$$\ddot{a} - a'' = -4g_{a\gamma}B_0 e$$

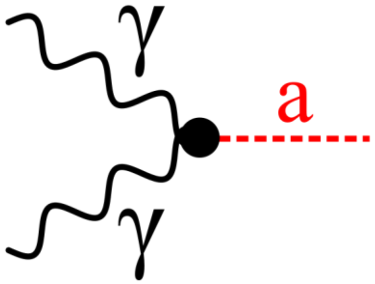
$$\ddot{e} - e'' = g_{a\gamma}a''B_0,$$

- Mode coupling of photons into plasma waves at the critical surface are described in a similar way.
- Parametric decay of gravitons into photons, axions into photons or vice versa are described by a similar set of equations. In this case the magnetic field is a propagating electromagnetic wave.

For $m_a \leq 1$ eV, stringent bounds are imposed by the CERN Axion Solar Telescope (CAST)

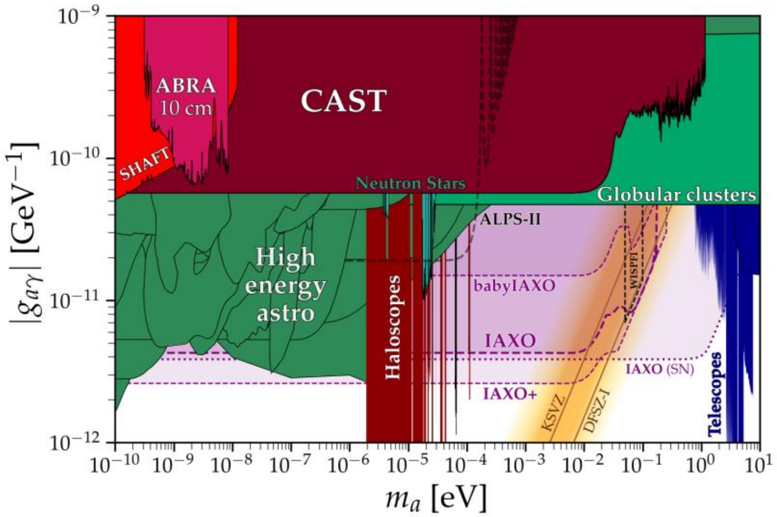
- <u>Helioscope</u>: Axions produced in the sun convert into photons via the Primakoff effect:

$$\mathcal{L}_{\text{axion}} = g_{a\gamma\gamma}\boldsymbol{E}\cdot\boldsymbol{B}a$$



- Geometry suppresses sensitivity to axions with $m_a > 1$ eV

- Some model dependence due to high temperature and ω_p in Solar plasma



CAST Collaboration, "*New CAST limit on the axion–photon interaction*" Nature Phys. **13**, 584 (2017).

J. Jaeckel *et al.* "*Need for purely laboratory-based axionlike particle searches*", Phys. Rev. D **75,** 013004 (2007)

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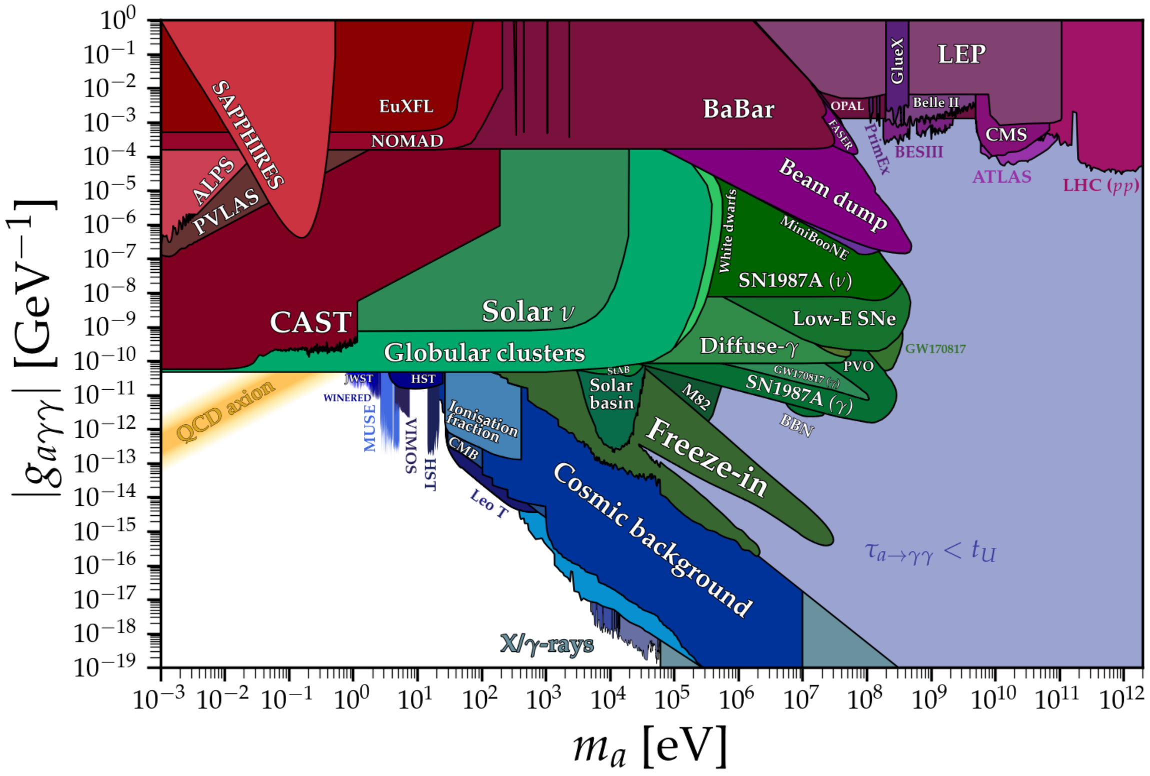

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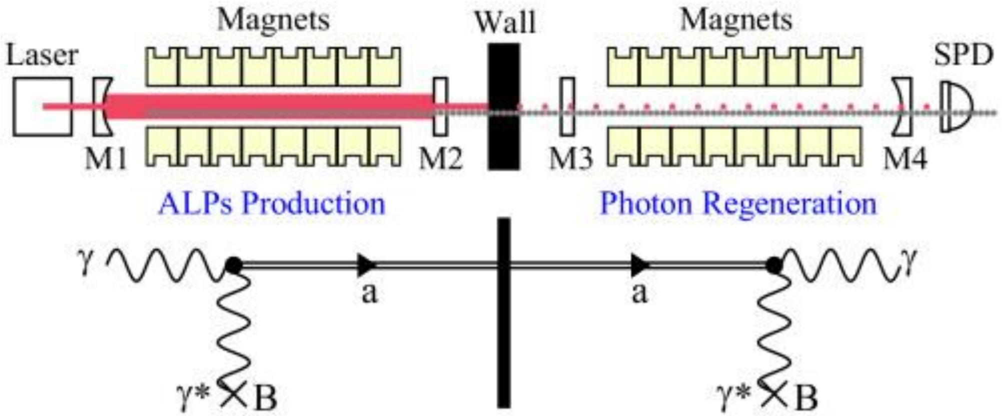
Credit: Ciaran O'Hare (github.com/cajohare/AxionLimits)

Light shining through wall (LSW) experiments are an example of direct detection searches

- Generating axions in the lab removes any model dependence
- But sensitivity suppressed by a factor of $\sim g_{a\gamma\gamma}$
- No sensitivity to $m_a > 1$ eV (uses visible photons)
- Photo taken from ALPS-II, current experiment at DESY which recycles magnets from HERA



C. Robilliard *et al, "No light shining through a wall",* Phys Rev. Lett. **99**, 190403 (2007).

Klaus Ehret *et al, "New ALPS results on hidden-sector lightweights",* Phys. Lett. B **689**, 149 (2010).

QSQAR collaboration, *"New exclusion limits on scalar and pseudoscalar axionlike particles"* Phys. Rev. D**92**, 092002 (2015).

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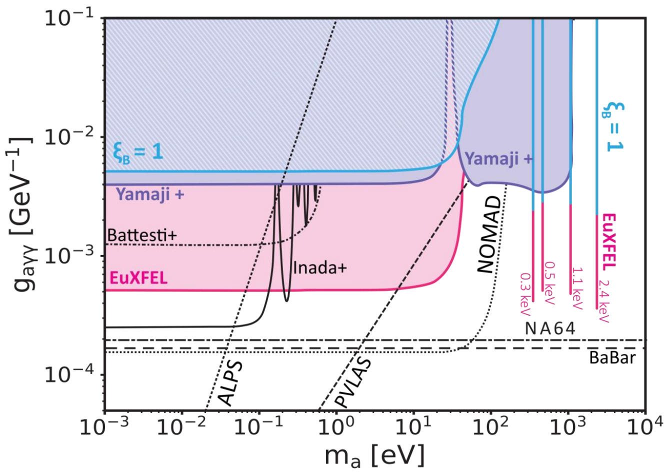
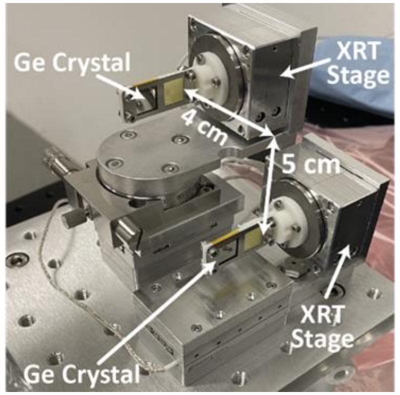


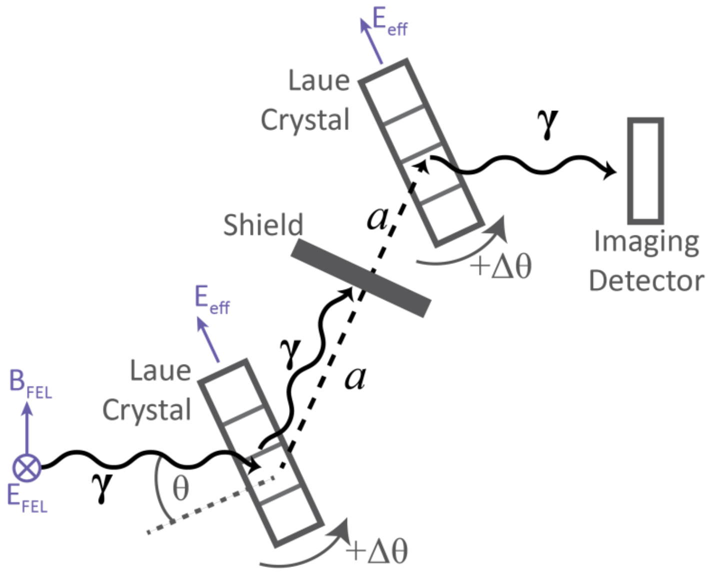


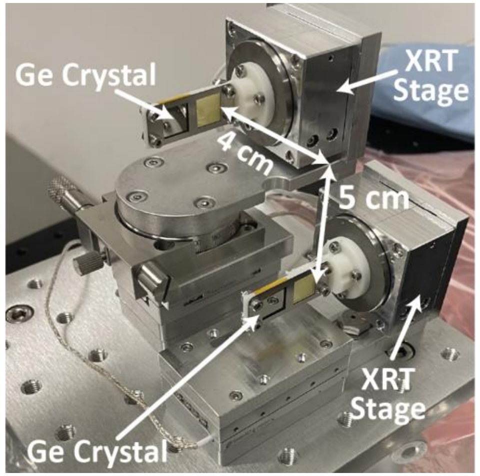
X-ray light sources enable the extension of light shining through wall experiments to search for heavy axions

- Again, rely on Primakoff effect:

$$\mathcal{L}_{\text{axion}} = g_{a\gamma\gamma}\boldsymbol{E}\cdot\boldsymbol{B}a$$

- Magnetic field from (σ-polarised) X-Ray beam
- Electric field normal to planes in crystalline material:
  - $E \sim 10^{11}$ V/m (equivalent to $B \sim 1$ kT)
  - Germanium crystal, thickness $L = 500$ μm
  - Path integrated field ~ 25 Tm
- Previous experiments [Yamaji+] on Synchrotron light source
- Our study is the *first* to use an X-Ray Free Electron Laser





Buchmüller & Hoogevee, *"Coherent production of light scalar or pseudoscalar particles in Bragg scattering"*, Phys. Lett. B **267**, 2 (1990).

T. Yamaji *et al*, *"Search for Axion like particles using Laue-case conversion in a single crystal"* Phys. Lett. B **782**, 526 (2018).

The sensitivity of the scan is a function of the interaction-length, while the mass range is tuned by adjusting θ

Probability of conversion:

$$P(a \leftrightarrow \gamma) = \left(\frac{1}{4} g_{a\gamma\gamma} E_{\text{eff}}\, L_{\text{eff}} \cos\theta_B\right)^2$$

$$L_{\text{eff}} = 2L_{\text{att}}^{B}\left[1 - \exp\left(-\frac{L_x}{2L_{att}^{B}}\right)\right], \quad L_x = \ell/\cos(\theta_B + \Delta\theta)$$

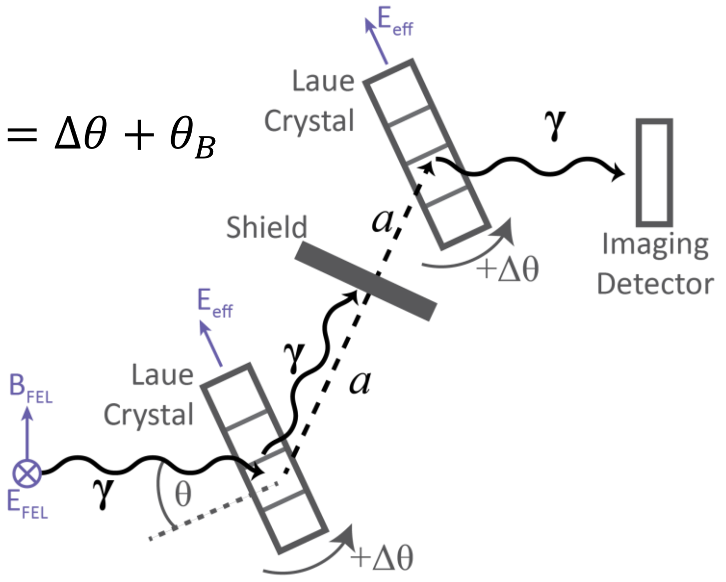
Mass range for the search:

$$\left|m_a^2 - m_\gamma^2\right| \le \frac{4k_\gamma}{L_{eff}} \qquad (\Delta\theta = 0)$$

$$m_a = \sqrt{m_\gamma^2 + 2q_T k_\gamma \cos(\theta_B)\Delta\theta} \qquad (\Delta\theta \neq 0)$$

T. Yamaji *et al, "Theoretical calculation of coherent Laue-case conversion between x-rays and ALPS for an X-ray LSW experiment"* Phys. Rev. D **96**, 15001 (2017).

$$\theta = \Delta\theta + \theta_B$$



Reciprocal lattice spacing (q_T)	6.2 keV
Plasma frequency (m_γ)	44 eV
Crystalline field (E_{eff})	7.3×10^{10} V/m
Attenuation length (L_{att}^{B})	1.5 mm
Crystal thickness (ℓ)	500 μm

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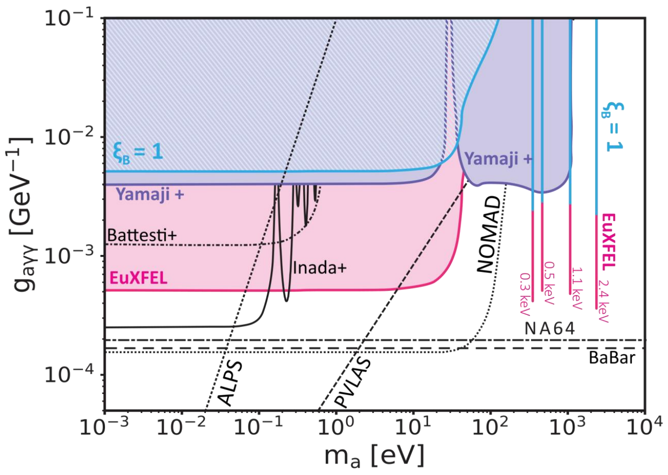
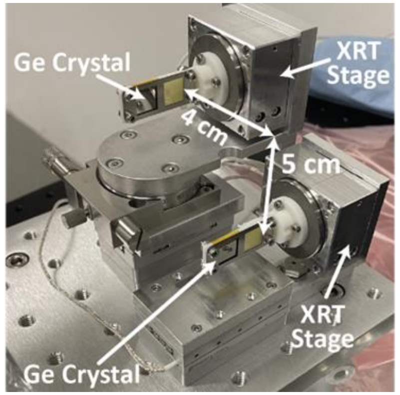
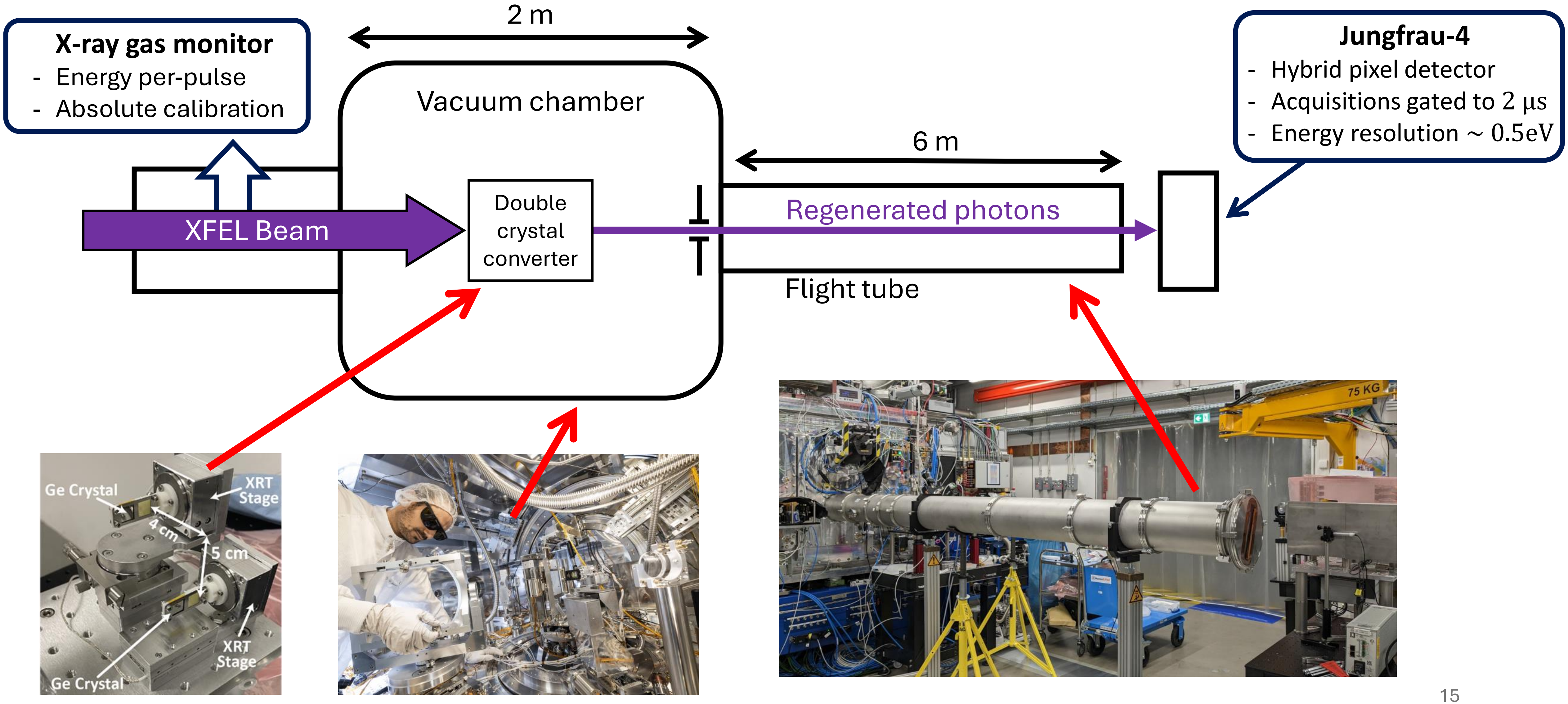
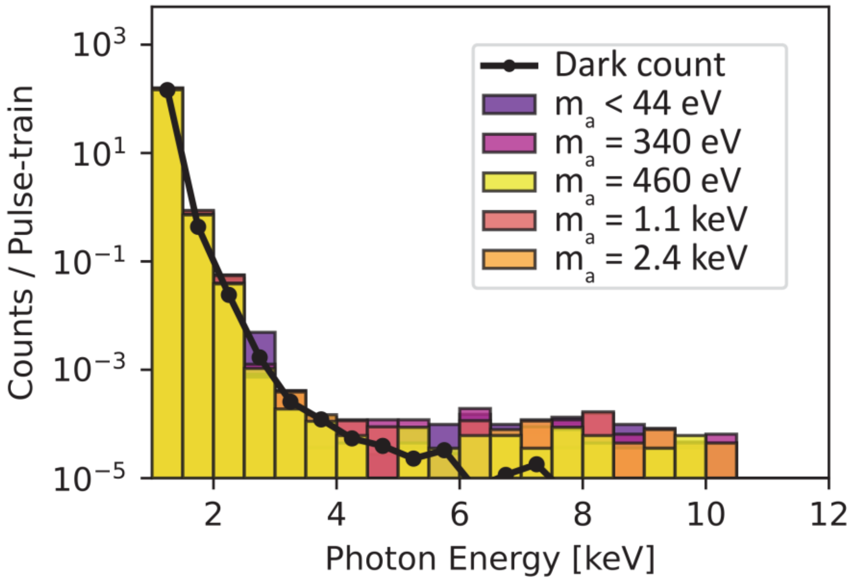


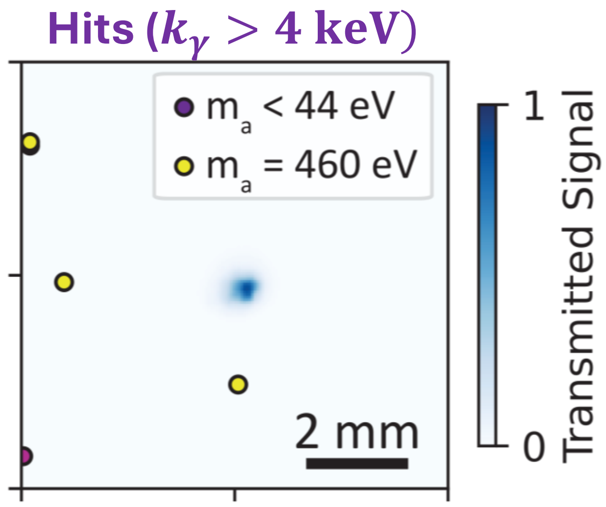


The XFEL instrumentation enabled an accurate constraint to be placed on input / output X-ray flux



Results *No events* consistent with axion production were detected during the experiment

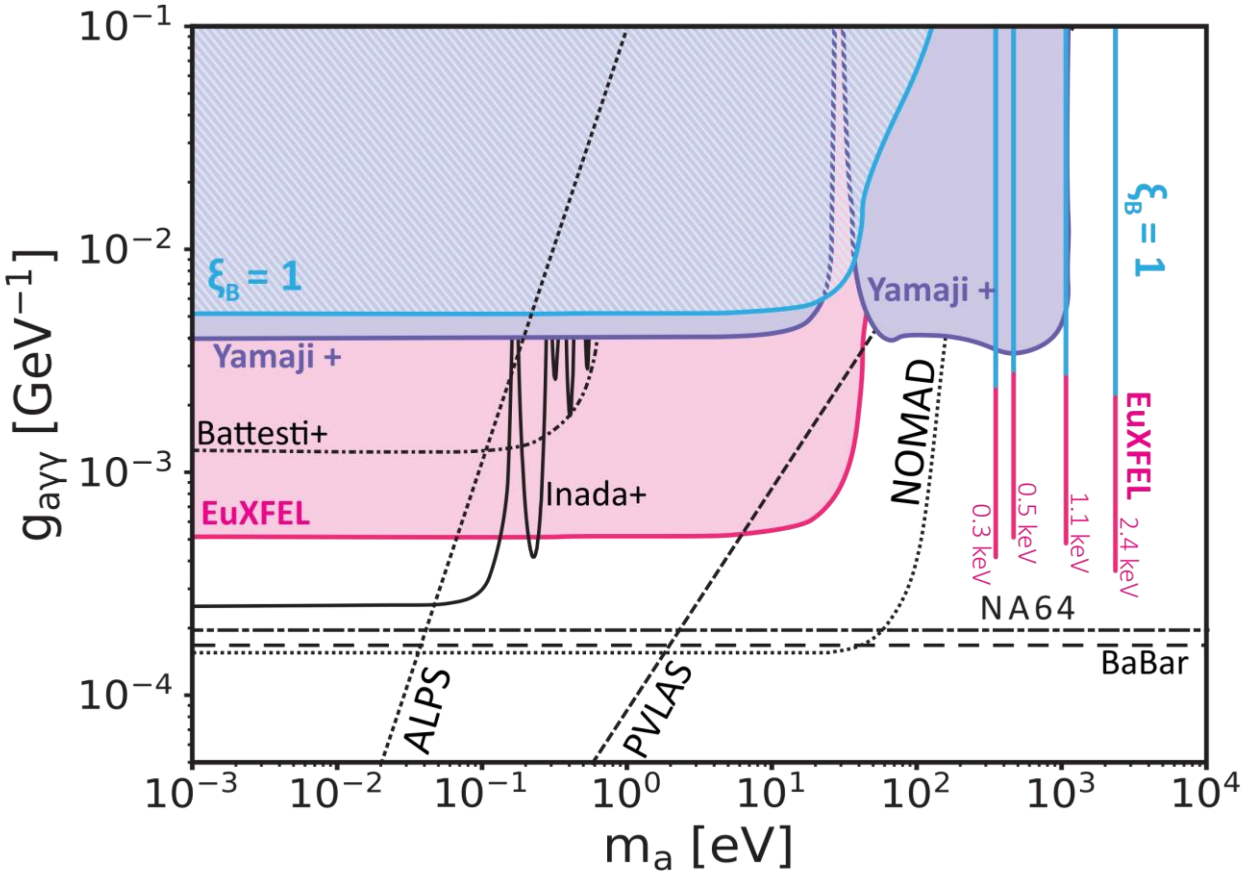




Events consistent with axion production have $k_\gamma = 9.8$ keV.

They should also lie on the X-ray spot observed on the Jungfrau when in characterisation mode.

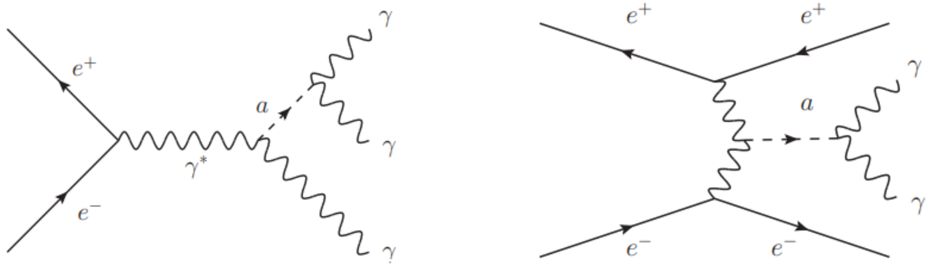
Bounds obtained in this work are competitive with existing studies - using a complementary search technique



J. W. D. Halliday *et. al. "Bounds on Heavy Axions with an X-Ray Free Electron Laser"* Phys. Rev. Lett. **134**, 055002 (2025)

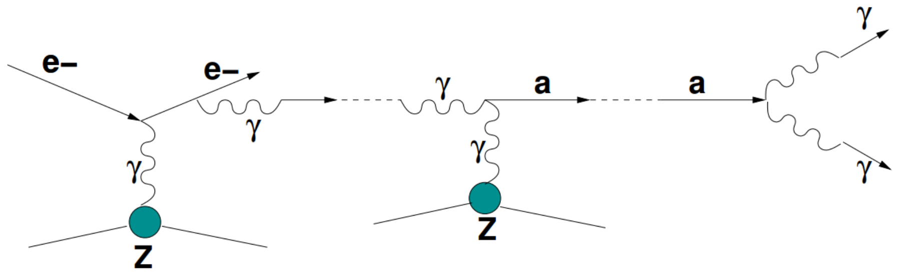
Our bounds are complimentary to those imposed from searches using accelerators

BaBar



- Bounds on dark photon detection [BaBar Collaboration] recast by Dolan *et al.* to obtain a bounds on $g_{a\gamma\gamma}$.
- Probes spontaneous axion decay

NA64



- Target-Bremsstrahlung photons generated by 100 GeV electrons in NA64 beam dump produce axions via the Primakoff effect
- Search for both spontaneous axion decay and missing energy in calorimetry data

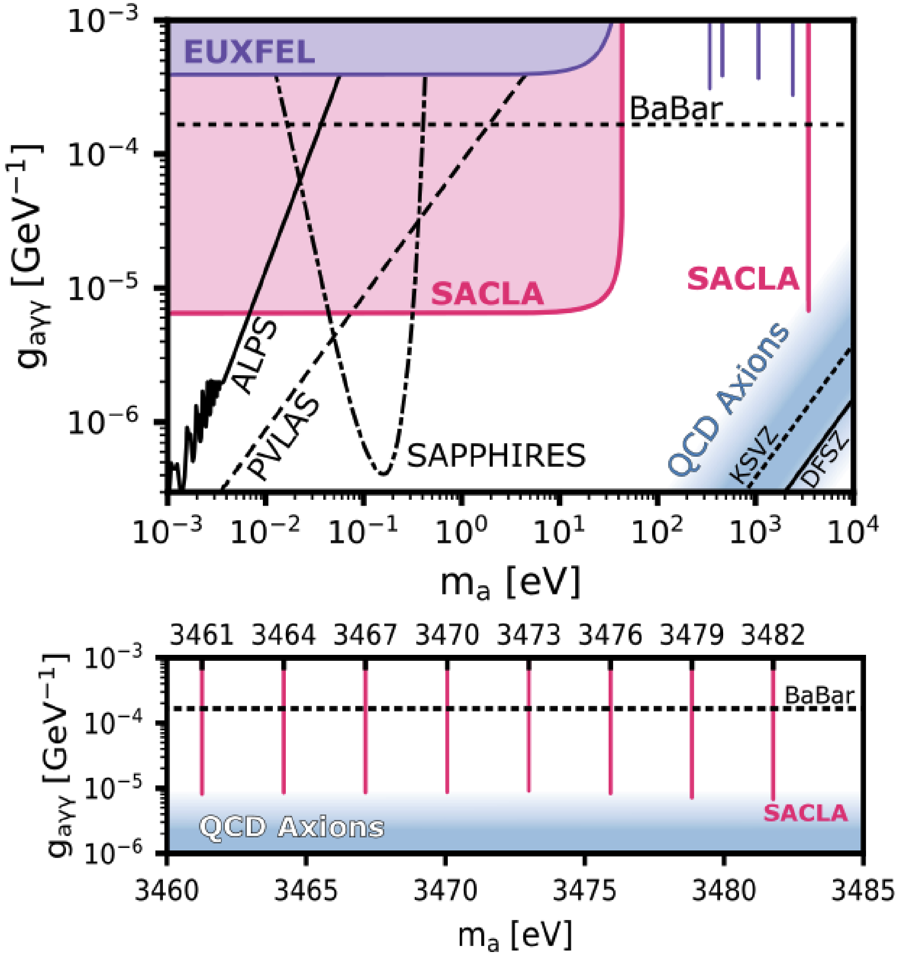
The BaBar collaboration. *“Search for Invisible Decays of a Dark Photon Produced in e^+e^- Collisions at BaBar”* , Phys. Rev. Lett. **119** (2017)

J. Dolan *et al. “Revised constraints and Belle-II sensitivity for visible and invisible axion-like particles”,* J. High Energ. Phys. 94 (2017)

The NA64 Collaboration, “Search for Axionlike and Scalar Particles with the NA64 Experiment” Phys. Rev. Lett. **125** (2020)

Follow-up SACLA measurements yield preliminary bounds approaching the QCD axion band

- Follow-up axion search performed at SACLA building directly on the EuXFEL configuration
- Operation in air enabled passive crystal cooling, allowing a deliberate trade-off of increased photon flux (~10^4) against reduced per-photon SNR
- Sensitivity was further improved through the use of thicker Germanium samples ($\ell \sim L^B_{\rm ext} = 1.5$ mm)
- Preliminary axion–photon coupling bounds extracted from 3 days of data collection (in October 2025)
- Sensitivity approaches the QCD axion band at discrete masses (off-Bragg scans)
- Future prospects: improved signal-to-noise and implementation of continuous mass scans via photon-angle tuning



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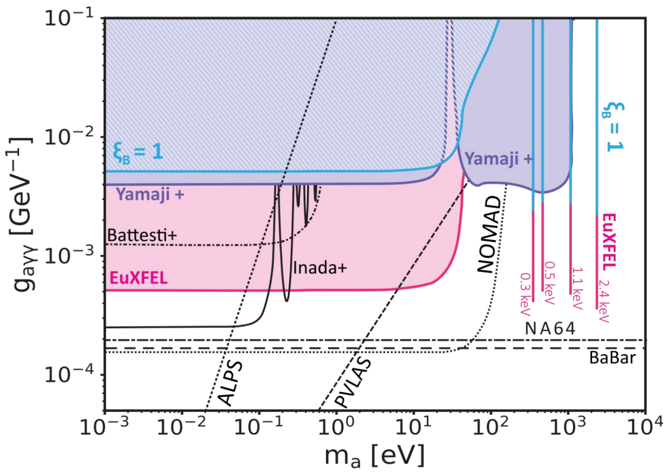
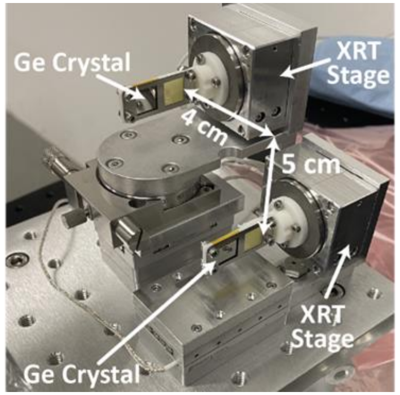
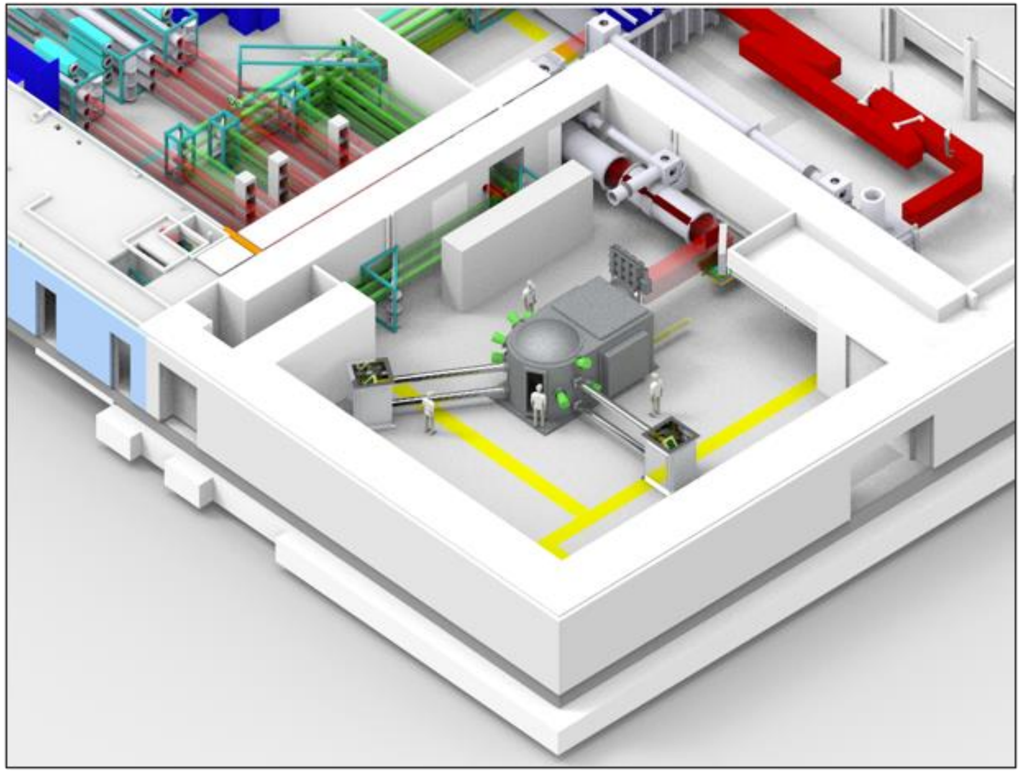




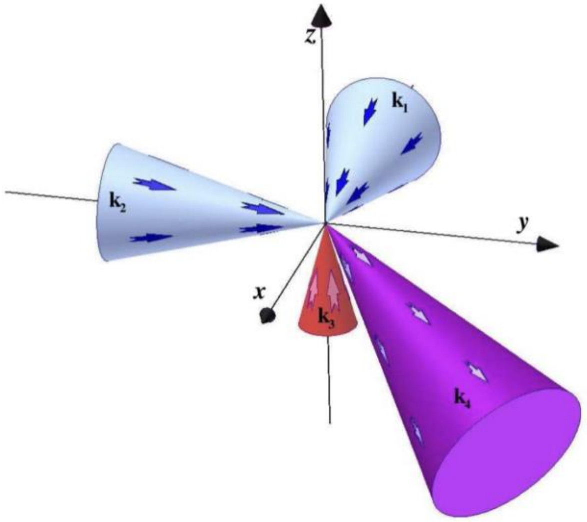
Vulcan 2020: Extreme Optical Fields for Strong-Field Experiments

- Optical laser system ($\lambda \sim 1\ \mu\text{m}, \varepsilon_\gamma \sim 1\ \text{eV}$)
- Primary beam will deliver 20 PW peak power in a 20 fs pulse
- Large-aperture beam ($\sim 650 \times 650\ \text{mm}^2$) focused to $\sim 5\ \mu m$, enabling peak intensities $\text{I} \gtrsim 10^{23}\ W/cm^2$
  ($\text{I}_{\text{Sch}} \sim 10^{29}\ \text{W/cm}^2$ but strong-field QED and perturbative non-linear vacuum effects accessible in targeted setups)
- Facility design explores splitting the primary beam into two equal arms, enabling dual-beam geometries
  (e.g. photon–photon interactions)
- Complemented by VOPPEL (1 PW-class) laser, optimised for laser-wakefield acceleration
  ($\sim 1\ GeV$ electron beams synchronised to the optical pulse with comparable spot size and duration)

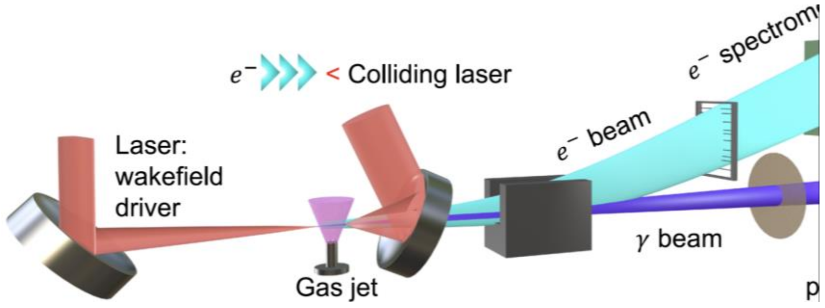


Selected Fundamental-Physics Experiments to Explore with Multi-PW Lasers

- **Simulated photon-photon scattering:** four-wave mixing scheme to detect elastic photon–photon scattering in vacuum using multi-PW lasers [E. Lundström *et al.*, "Using high-power lasers for detection of elastic photon–photon scattering," *Phys. Rev. Lett.* **96**, **083602** (2006).]



- **Quantum radiation reaction:** high-significance ($> 5\sigma$) experimental validation of quantum radiation-reaction models in laser-electron collisions at strong fields [E. E. Los *et al.*, "Observation of quantum effects on radiation reaction in strong fields," *Nat. Commun.* **17**, 1157 (2026).]



- **Axion photon / axion electron coupling:** exploratory experimental concepts.
- **Longer-term directions:** Exotic atoms; Post Newtonian gravity; high-frequency gravitational wave detection…

Parametric co-linear axion photon instability

- Axions and axion-like particles generically couple to QED via the axion-photon-photon interaction. This leads to a modification of Maxwell's equations known in the literature as axion-electrodynamics.

- The new form of Maxwell's equations gives rise to a new parametric instability in which a strong pump decays into a scattered light wave and an axion. This axion mode grows exponentially in time and leads to a change in the polarisation of the initial laser beam, therefore providing a signal for detection.

- Currently operating laser systems can put bounds on the axion parameter space, however, longer pulse lengths are necessary to reach the current best laboratory bounds of light-shining through wall experiments.

- We will demonstrate the existence of a new parametric decay instability of one photon in the seed pulse into an axion and a secondary photon, satisfying

$$\omega_0 = \omega_\gamma + \omega_a \qquad \text{and} \qquad \mathbf{k}_0 = \mathbf{k}_\gamma + \mathbf{k}_a.$$

Beyer et al PRD, 839, 137759, 2023

Nonlinear photon axion coupling

Axions generically couple to Standard Model photons via the Lagrangian

$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B},$$

The axion-photon vertex (1) introduces a source and current to the vacuum Maxwell's equations

$$\nabla \cdot \mathbf{E} = g_{a\gamma\gamma} (\nabla a) \cdot \mathbf{B},$$
$$\nabla \cdot \mathbf{B} = 0,$$
$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B},$$
$$\nabla \times \mathbf{B} = \partial_t \mathbf{E} + g_{a\gamma\gamma} (\mathbf{E} \times \nabla a - \mathbf{B} \partial_t a) .$$

We employ Coulomb gauge $\nabla \cdot \mathbf{A} = 0$, and work in the *colinear* limit where all momenta, are parallel to find the wave equations for the gauge potentials

$$\left(\partial_t^2 - \nabla^2\right) \mathbf{A} = g_{a\gamma\gamma} \nabla \times (a \partial_t \mathbf{A}) \quad (5)$$

and

$$\nabla^2 \phi = 0. \quad (6)$$

In this colinear limit, we may use the residual gauge freedom to set $\phi = 0$. The remaining equation of motion for the axion is then

$$\left(\partial_t^2 - \nabla^2 + m_a^2\right) a = g_{a\gamma\gamma} (\partial_t \mathbf{A}) \cdot (\nabla \times \mathbf{A}). \quad (7)$$

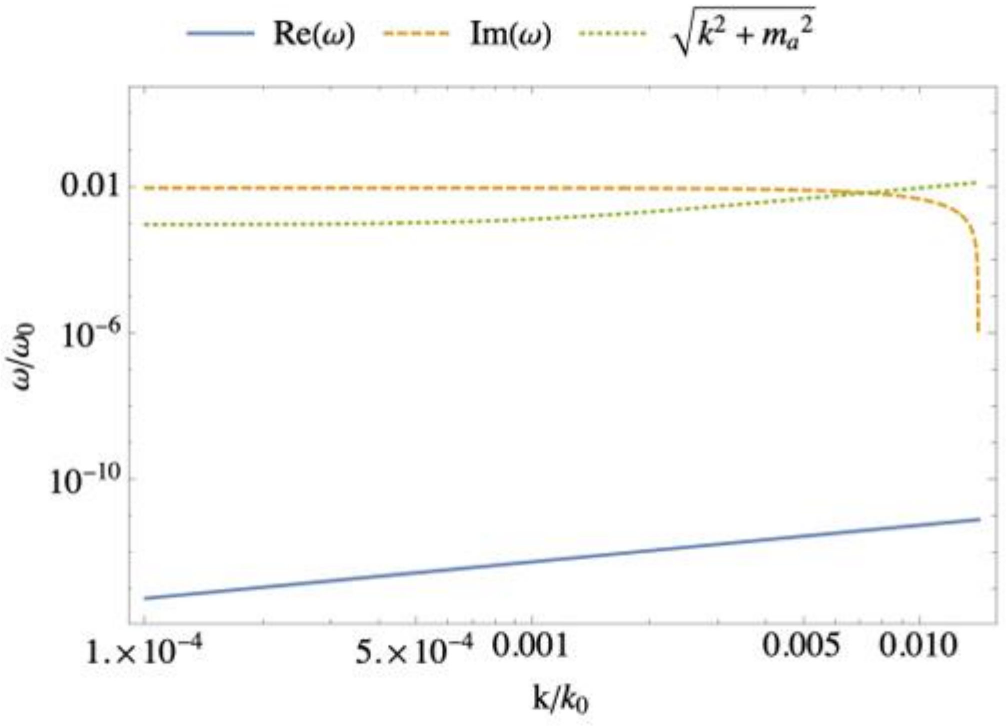
Equations 5-7 describe the nonlinear coupling between the photons and axions

A stability analysis yield the dispersion relation

$$D^a(\omega, k) = \frac{g_{a\gamma\gamma}^2 A_0^2}{4} \omega_0 (\omega_0 k - \omega(k) k_0) \left(\frac{k_-}{D_-^\gamma} + \frac{k_+}{D_+^\gamma} \right).$$

where $k = |\mathbf{k}|$, $D^a(\omega, k) \equiv \omega^2 - k^2 - m_a^2$, $D_\pm^\gamma \equiv (\omega \pm \omega_0)^2 - (k \pm k_0)^2$,

Nonlinear photon axion coupling



K Beyer et al Phys. Lett B 839,137759,2023

The plot shows the growing solution to the dispersion relation.

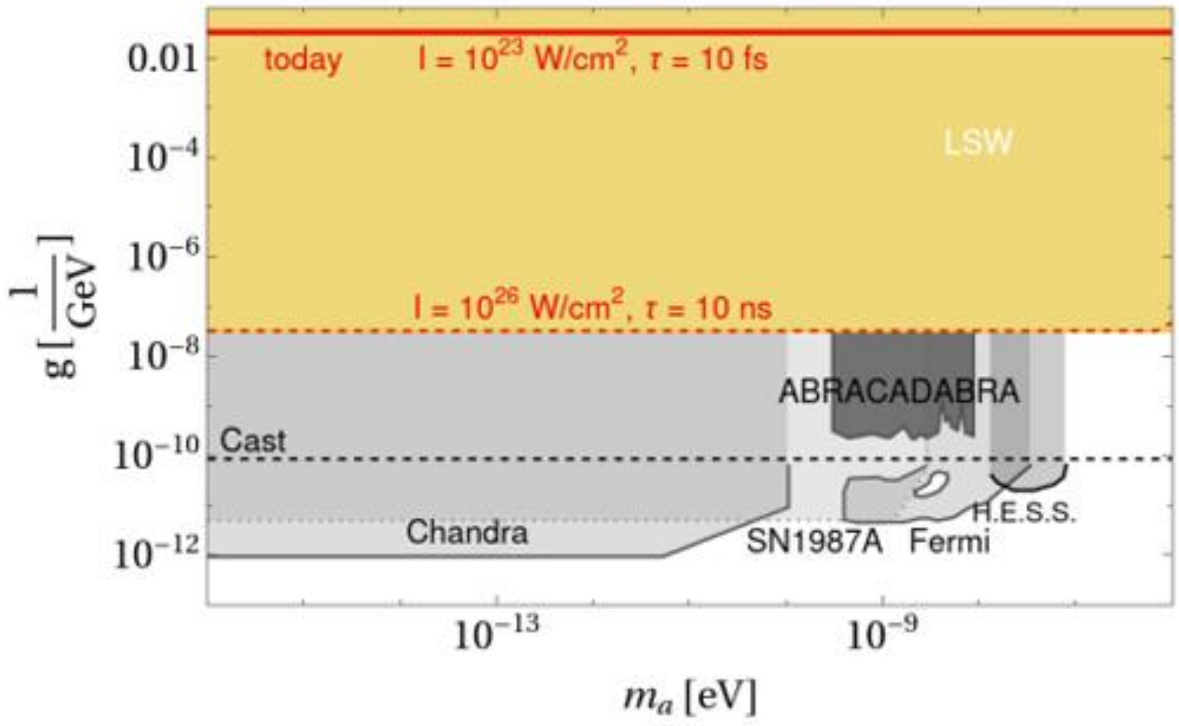
The blue solid curve shows the real part $\omega_a(k)$ corresponding to the frequency while the dashed yellow curve depicts the growth rate.

As a reference we include the vacuum dispersion relation for an axion with the same mass in dotted green.

For illustration purposes we have chosen $m_a/\omega_0 = 10-3$ and $g_{a\gamma\gamma}A_0 = 10-3$.

We see that even for such large values, the axion frequency is negligibly small.

Nonlinear photon axion coupling



Axion exclusion plot indicating past experiments and the nonlinear photon axion coupling.

To reach the sensitivities of present experiments and satellite measurements requires laser intensities greater than 10^{26} W/cm^{-2} and pulse lengths of ns.

K Beyer et al Phys. Lett B 839,137759,2023

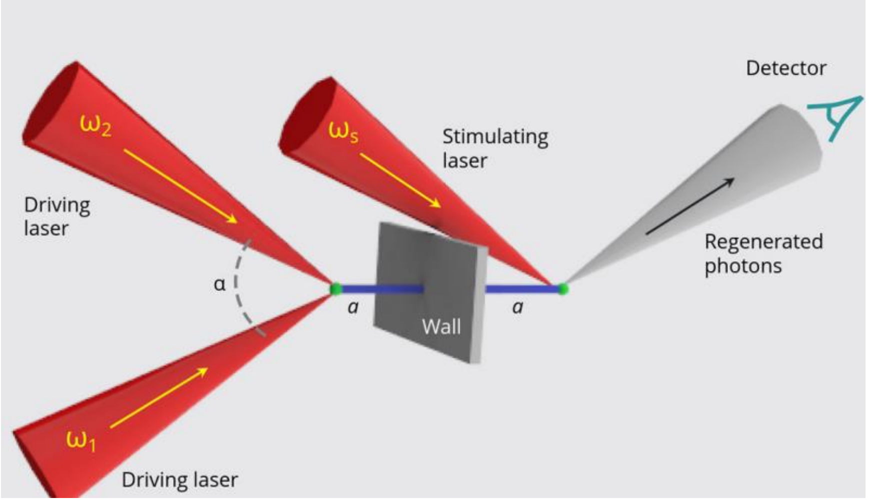
Axion search, with optical lasers, sensitive to $m_a = 1 - 10\ \text{eV}$

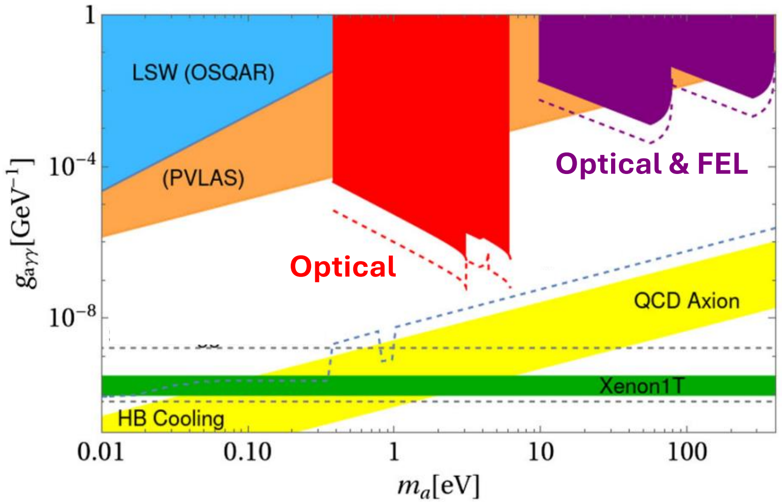
- Two short-pulse optical laser beams with orthogonal polarisations crossed in vacuum
- Axion production via the axion–photon interaction:

$$L_{\text{axion}} = g_{a\gamma\gamma} \boldsymbol{E} \cdot \boldsymbol{B} a$$

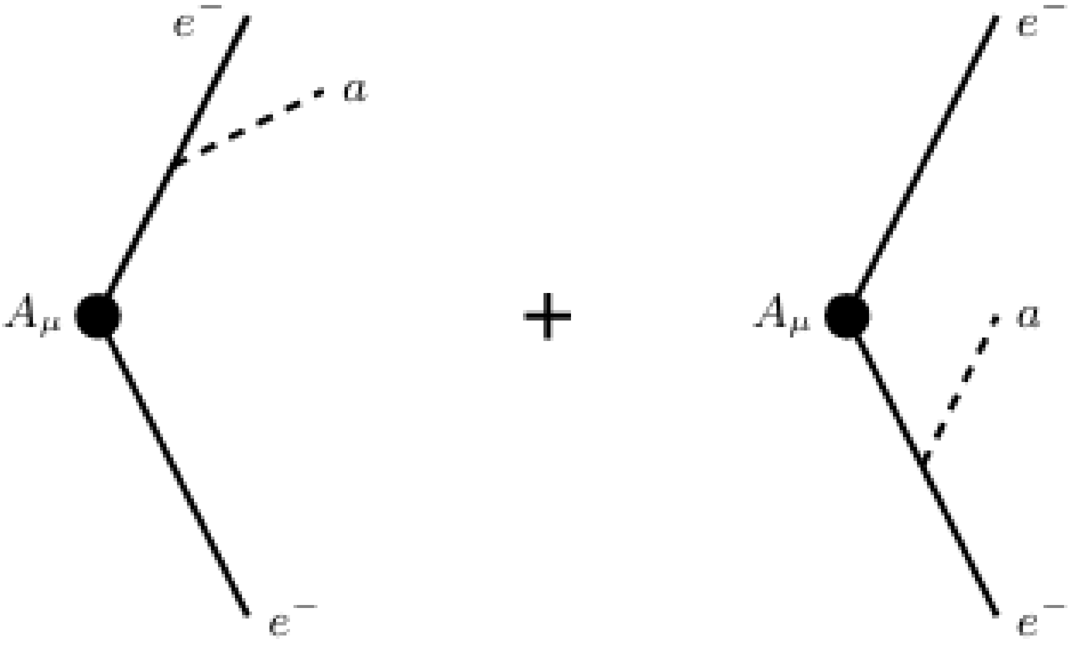
- Axions reconverted to photons via the inverse process using a third (stimulating) beam (LSW geometry)
- Projected sensitivity shown for the Aton-4 laser (ELI, Czech Republic) in the 1-10 eV mass range
- The same experimental concept is directly adaptable to multi-PW optical facilities including Vulcan-2020

K. Beyer *et al.* *"Light-shining-through-wall axion detection experiments with a stimulating laser"* Phys. Rev. D **105**, 035031 (2022)





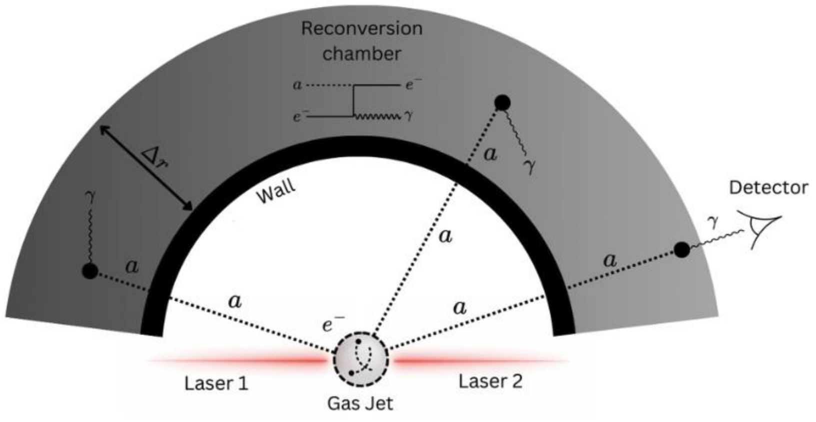
Axion emission from laser accelerated electrons

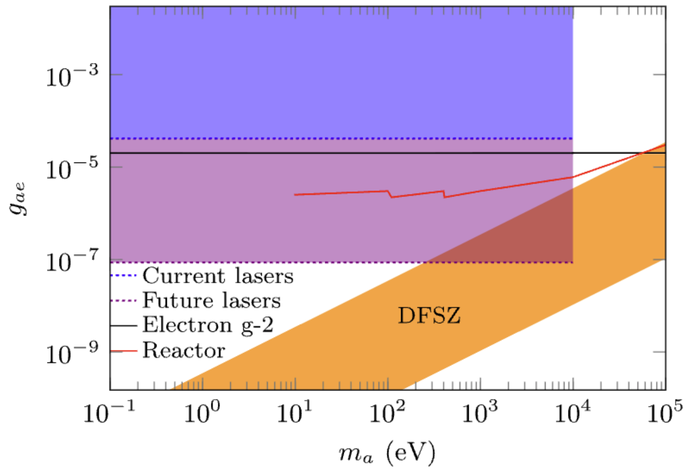


- The Feynman diagrams for the axion emission:
- The solidlinerepresents the electron and the dashed line represents the axion.
- The dot represents the interactionof the electron with the laser

Laser-driven schemes targeting the axion–electron coupling

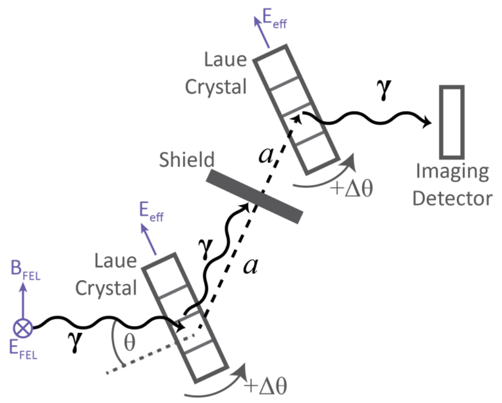
- Two counter-propagating laser pulses form a standing wave in a gas jet, directly accelerating electrons via the oscillating electric field.
- Accelerated electrons have a probability to emit axions during this direct acceleration process (by analogy with radiation from an accelerated charge)
- Axions traverse through a wall and interact with electrons in the material, enabling reconversion via a Compton-like process ($a + e^- \rightarrow \gamma + e^-$)
- Projected sensitivities for multi-PW laser facilities are competitive with existing accelerator searches

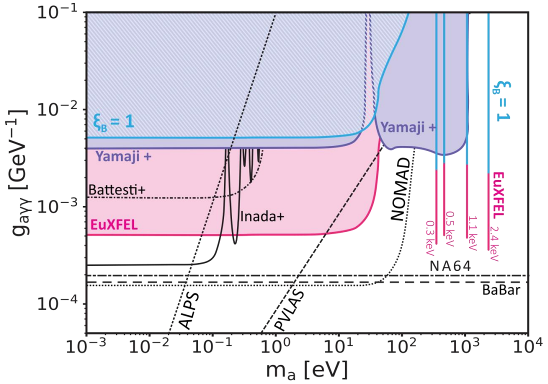


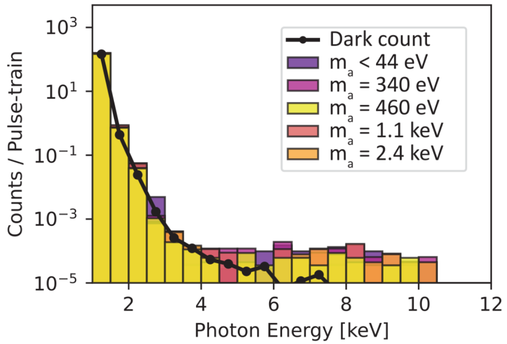


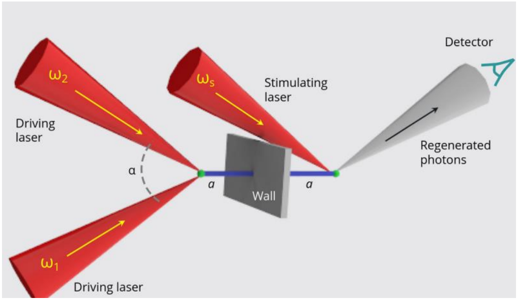
G. Vacalis, A. Higuchi, R. Bingham, and G. Gregori, *Proposal to use laser-accelerated electrons to probe the axion–electron coupling*, **Phys. Rev. Lett. 135**, 195003 (2025).

Conclusions









- Axions explain the absence of CP-violation in strong interactions and are a cold dark matter candidate
- We performed a search for heavy axions on EuXFEL and SACLA.
- Had issues with crystal heating, but we could still impose competitive bounds on $g_{a\gamma\gamma}$ using a search technique complimentary to collider-based experiments
- Follow up experiments using high power laser eg Vulcan.
- High powered lasers have potential uses for fundamental physics, including in axion searches.

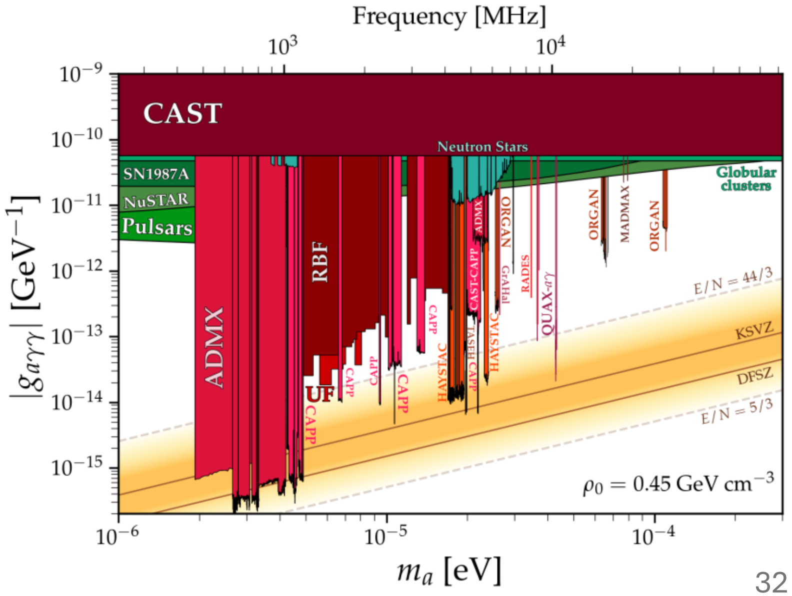
J. W. D. Halliday *et. al.* *"Bounds on Heavy Axions with an X-Ray Free Electron Laser"* Phys. Rev. Lett. **134**, 055002 (2025)

Thank you

In the $m_a \sim \mu\text{eV}$ region, haloscopes, including ADMX, probe down to the QCD axion coupling.

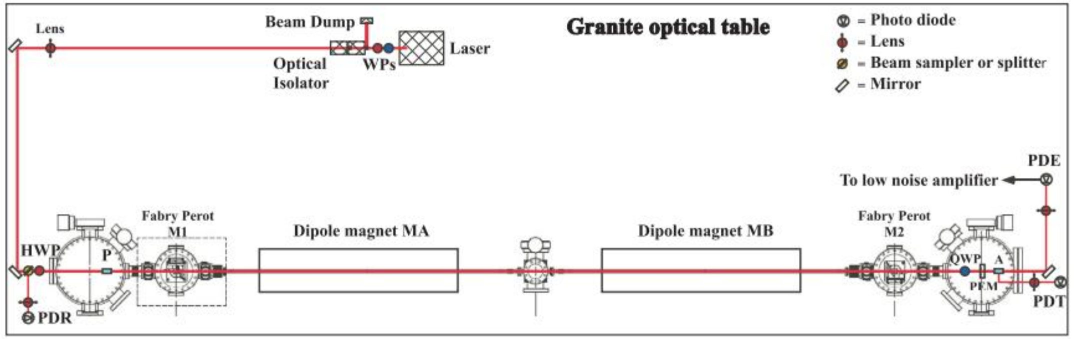
- Axion Dark Matter eXperiment (ADMX), at the University of Washington
- <u>Haloscope</u>: Axions from (local) Galactic halo convert to microwaves in cavity surrounded by a super-conducting electromagnet ($\mathrm{B} = 7.6\ \mathrm{T}$)
- Tune cavity Q-factor to scan through different axion masses
- Probes down to QCD axion couplings for $m_a = 1 - 100\ \mu\text{eV}$

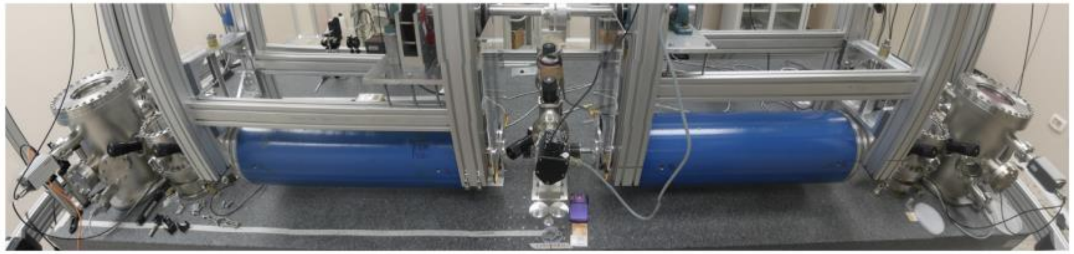
C. Goodman *et al, "Axion dark matter experiment around 3.3 eV with Dine-Fischler-Srednicki-Zhitnitsky discovery ability"*, Phys. Rev. Lett. – in press (2025)

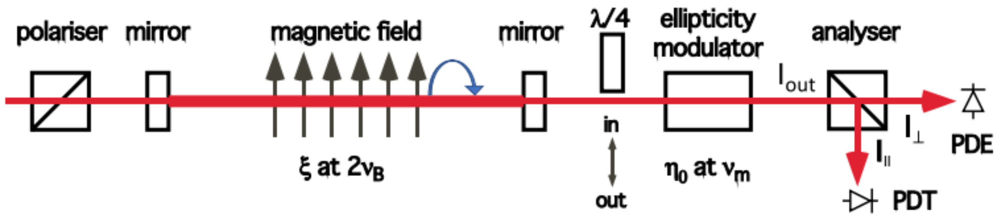


Vacuum birefringence experiments, including PVLAS, are also sensitive to axions generated terrestrially

- Vacuum birefringence – induce ellipticity in laser propagating though magnetic field
- Sensitive to a variety of QED effects (e.g. photon-photon scattering)
- Axion-photon coupling can also induce ellipticity
- Sensitive to <u>generation</u> of axions, *not* <u>regeneration</u> of photons:
    - $P_{a\leftrightarrow\gamma} \propto (g_{a\gamma\gamma})^1$ – Vacuum birefringence
    - $P_{a\leftrightarrow\gamma} \propto (g_{a\gamma\gamma})^2$ – LSW experiments
- Hard limit on sensitivity due to QED effects





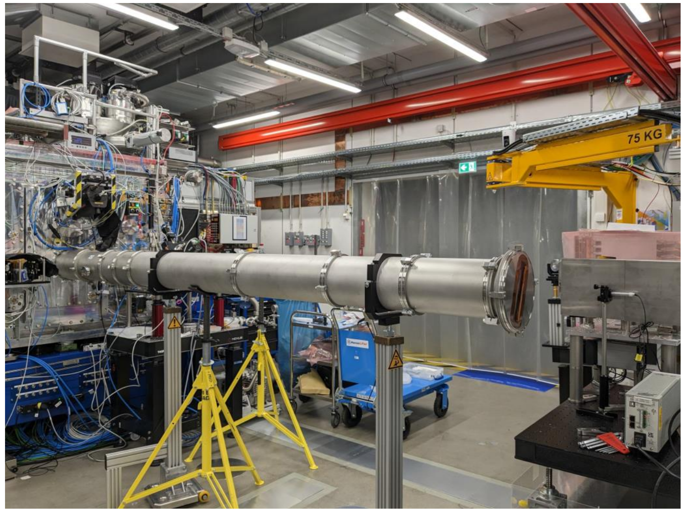


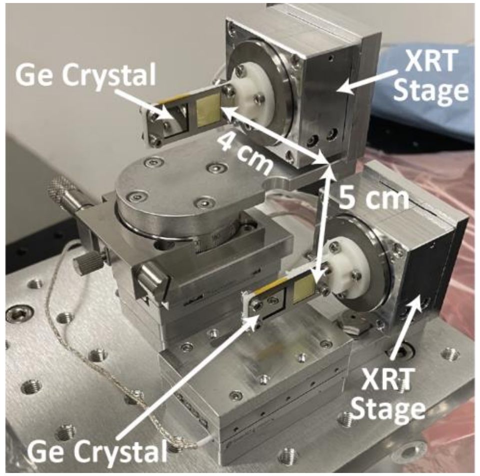
A. Ejlli *et al*, *"The PVLAS experiment: A 25 year effort to measure vacuum magnetic birefringence"* Phys. Rep. **871**, 1 (2020).

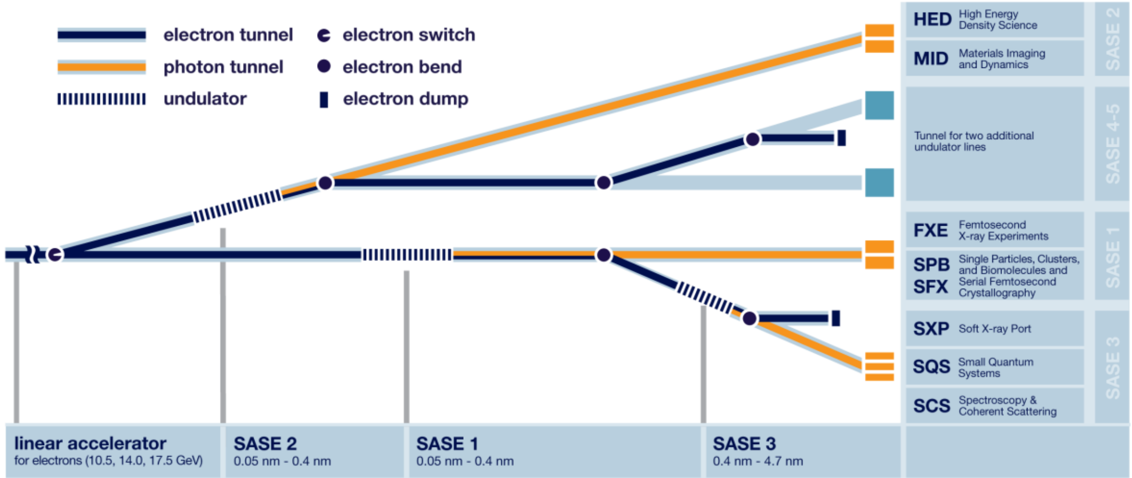
Configuration used for our experiment at The European XFEL (EuXFEL)

- Our search used the HED/HiBEF instrument at EuXFEL, Hamburg
- Three days (72 hrs) of beamtime awarded over the Easter bank holiday 2023
- Operated in a self-seeded mode

Parameter	Value
Photon energy / wavelength	9.8 keV / 1.3 Å
Bandwidth ($\Delta E/E$)	5×10^{-5}
Pulse duration	$\sim 10^{-14}$ s
Repetition rate	10 Hz
Spot size	$400 \times 400\ \mu m^2$
Total photons on-target	1×10^{17}







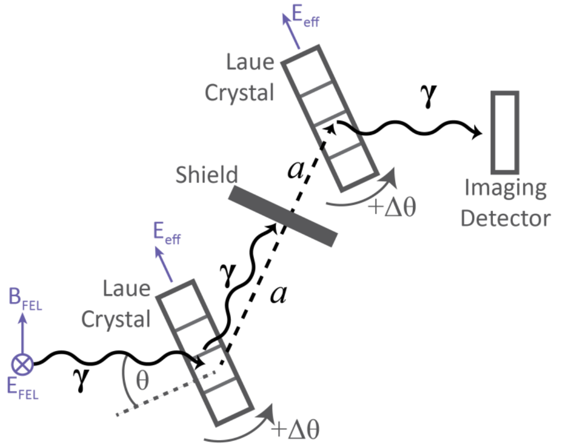
The Borrmann effect increases the extinction length by $\sim 10^3$ for Laue-case diffraction

- Conversion probability - $P(a \leftrightarrow \gamma) \propto L_{ext}^2$
- **Laue-case diffraction**
  - Scatter off planes normal to crystal surface
  - Anomalous extinction, $L_{\text{ext}}^B = 1500\ \mu\text{m}$
  - Due to the Borrmann effect
- **Bragg case diffraction**
  - Scatter off planes parallel to crystal surface
  - Extinction, $L_{\text{ext}} = 1\ \mu\text{m}$
- In both cases diffraction follows Bragg's law

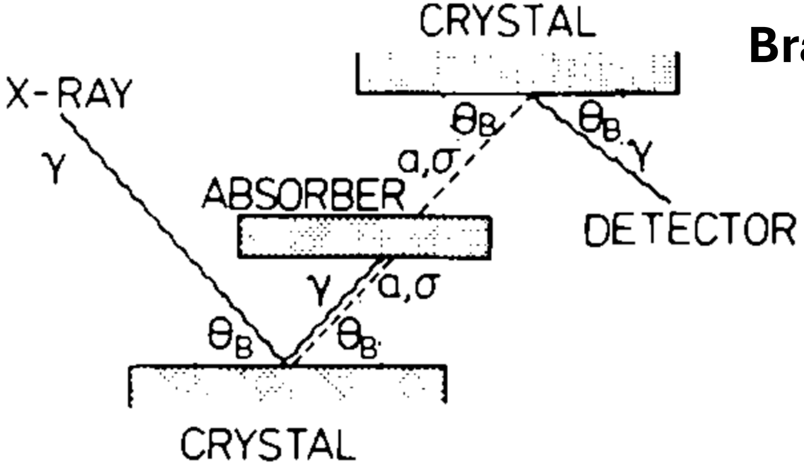
$$2d\sin\theta_B = n\lambda$$

G. Borrmann *"Über Extinktionsdiagramme von Quarz"* Physikalische Zeitschrift **42** (1941).

Laue



Bragg



[Buchmüller & Hoogeveen – 1990]

For XFEL experiments, the pulse duration is short compared to the timescale associated with diffraction

- Consider 2 measures of angular spread of transmitted X-rays:

Rocking curve width ($\Delta\theta_{RC}$): *Actual* angular spread

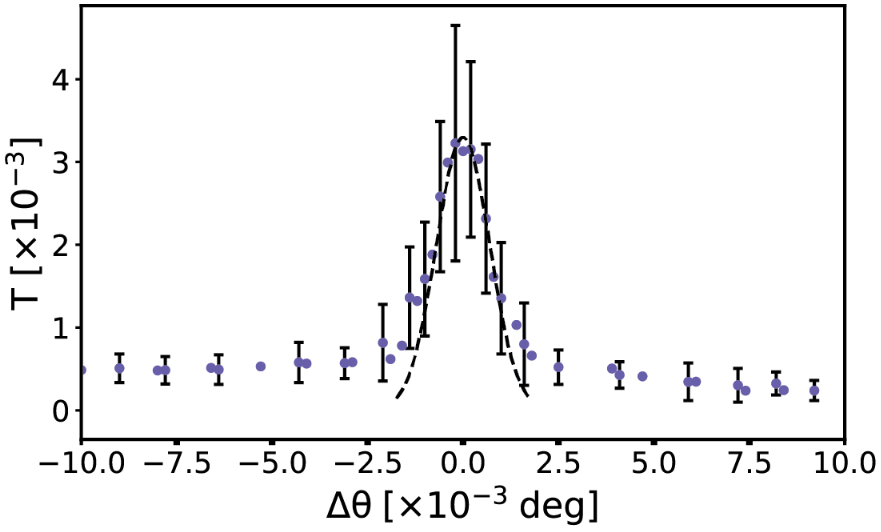
Darwin width ($\Delta\theta_D$): *Predicted* spread using a theory that neglects time dependence

- For a transform limited pulse:

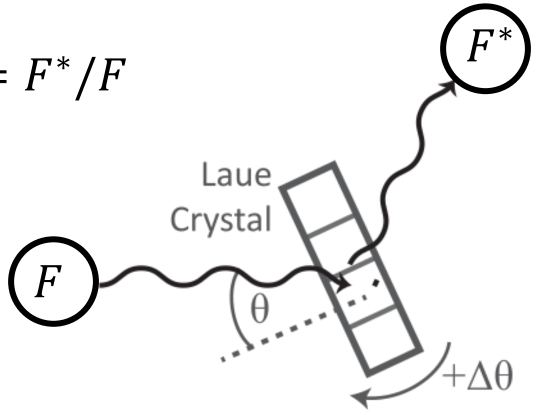
$$\Delta\theta_{RC}\Delta t \approx \frac{\lambda_x \tan\theta_B}{c}$$

- The timescale for diffraction is:

$$\Delta t = (2\ell/\mathrm{c})\tan\theta_B \sin\theta_B$$



$T = F^*/F$



Wark & Lee, "*Simulations of femtosecond X-ray diffraction from unperturbed and rapidly heated single crystals*", Journal of Applied Crystallography **32** (1999).

Probability for photon-axion conversion should account for this short pulse-duration

- There is an implicit assumption in theory from Yamaji *et al.* that $\Delta\theta_{RC} = \Delta\theta_D$
- Expression for conversion probability modified to account for this:

$$P(a \leftrightarrow \gamma) \approx \left(\frac{1}{4} g_{a\gamma\gamma} \xi_B E_{\text{eff}}\, L_{\text{eff}} \cos\theta_B\right)^2$$

$$\xi_B = \Delta\theta_D / \Delta\theta_{RC}$$

- Time-bandwidth product – expression accurate to factor of order unity
- Physical interpretation: increase in refractive index of crystal

T. Yamaji *et al, "Theoretical calculation of coherent Laue-case conversion between x-rays and ALPS for an X-ray LSW experiment"* Phys. Rev. D **96**, 15001 (2017).

Rocking curve width ($\Delta\theta_{RC}$): *Actual* angular spread of transmitted X-rays

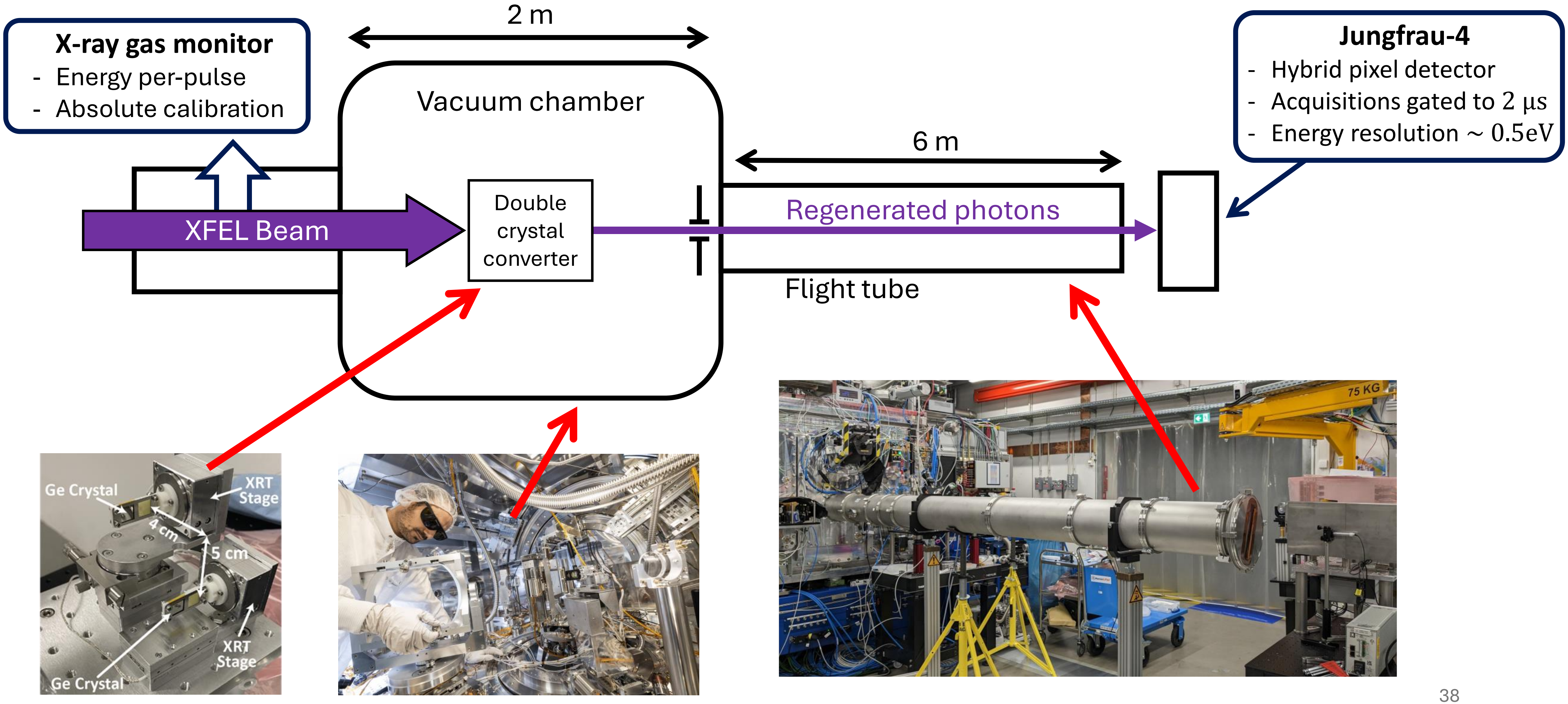
Darwin width ($\Delta\theta_D$): *Predicted* spread using a theory that neglects time dependence

Rocking curve width ($\Delta\theta_{RC}$)	~ 0.4 μrad
Darwin width ($\Delta\theta_D$)	44 μrad
ξ_B	~ 110

"Brilliance" of XFEL amplifies conversion probability

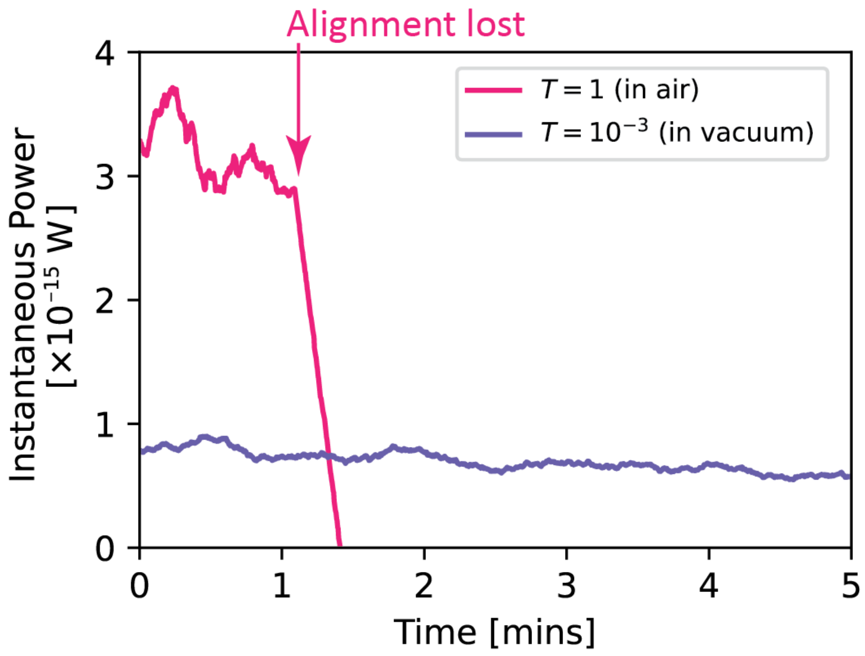
$(N_\gamma/\,\text{mm}^2/\,\text{s}/\text{mrad}^2/\,0.1\%\text{BW})$

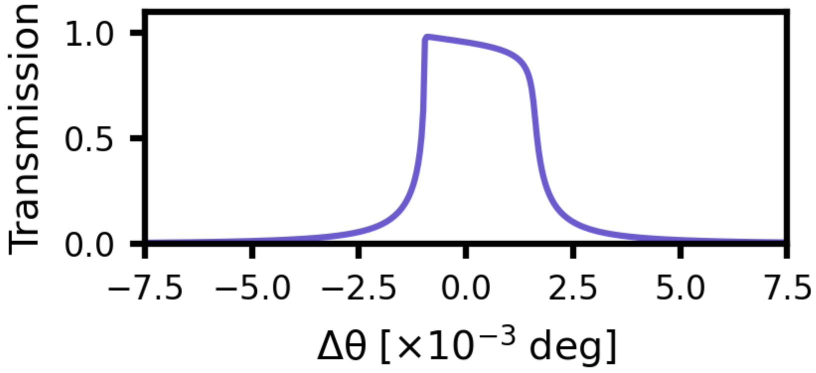
The HED/HiBEF instrumentation enabled an accurate constraint to be placed on input / output X-ray flux



Crystal heating was a major problem during the beamtime

- Maintaining alignment is challenging as the heat load distorts the crystal lattice
- Rocking curve width for Germanium $\sim 5 \times 10^{-3}$ degrees
- Able to maintain stable alignment with 10^3 attenuation applied to the XFEL beam
- Limited search to acquiring data at θ_B and at 4 discrete values of $\Delta\theta$
- In future experiments can mitigate:
  - Active cooling of conversion crystal





Due to crystal heating, a multi-step process was used for data collection

- Process for data collection:
    1. Stages tuned to θ_B and radiation shield removed. ~2 mins characterization data collected.
    2. Stages tuned to search angle & radiation shield returned. ~10 mins search data collected.
    3. Stages tuned back to θ_B and shield removed. ~2 mins characterization data collected.
- For the i'th run calculate:

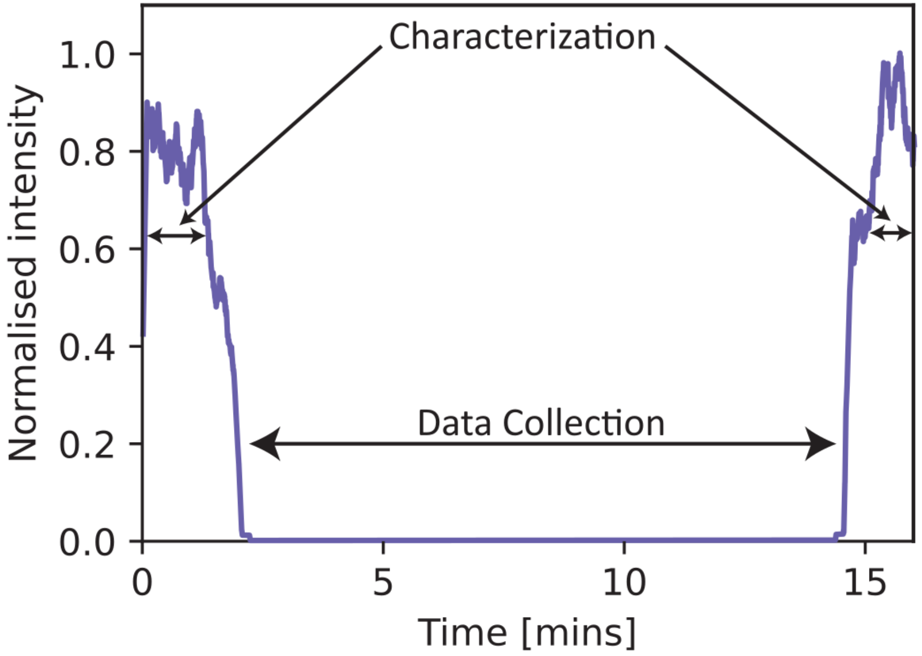
$$\eta_i = \frac{1}{T_{\mathrm{Ge}}^2} \frac{E_i^{\mathrm{JF,ch}}}{E_i^{in,ch}}$$

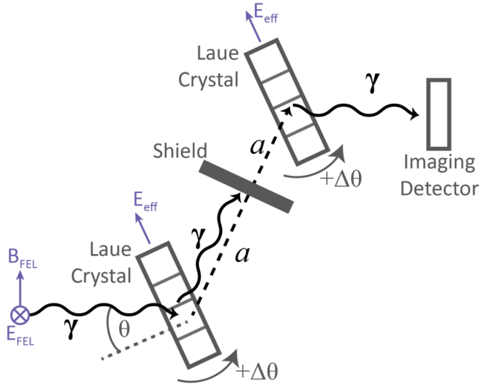
- Then, for all runs at a given $\Delta\theta$:

$$\eta N_{in} = \sum_i \eta_i E_i^{\mathrm{in,aq}} / k_\gamma$$

- Measured probability of axion generation then:

$$P(a \leftrightarrow \gamma)^2 = \frac{N_{\mathrm{det}}}{\eta N_{in}}$$





Bounds on the coupling strength were calculated taking a 90% confidence interval

- Measured probability of axion generation:

$$P(a \leftrightarrow \gamma)^2 = \frac{N_{\mathrm{det}}}{\eta N_{in}}$$

- Take $N_{\mathrm{det}} = 2.3$ events (assume events Poisson distributed, 90 % confidence interval with $\mu = 0$)
- Upper bound on axion-photon coupling:

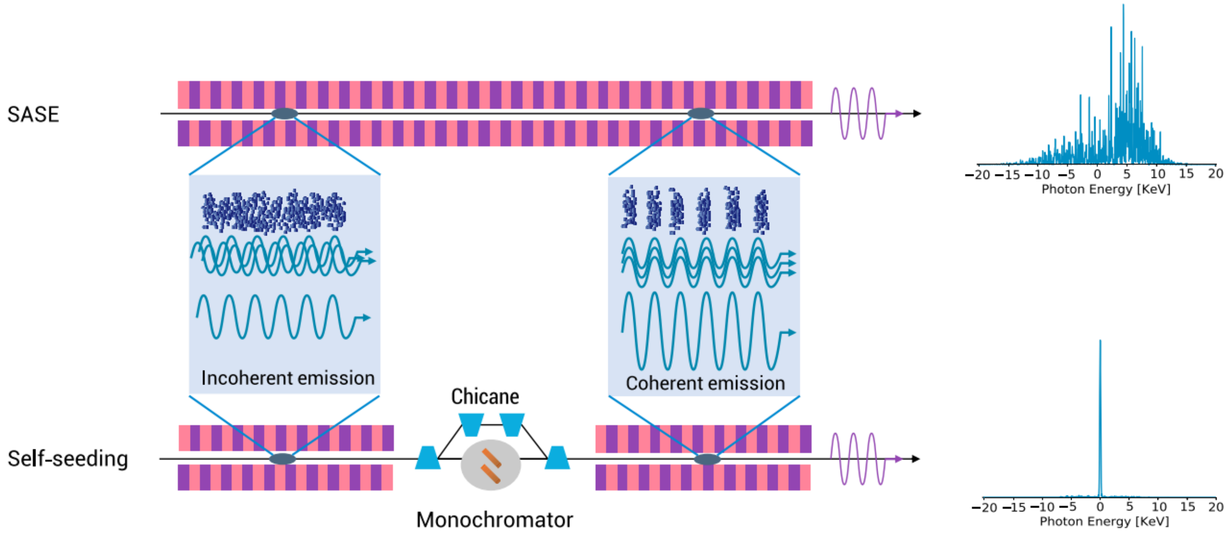
$$g_{a\gamma\gamma} < \left(\frac{1}{4} E_{\mathrm{eff}} L_B \xi_B \cos\theta_B\right)^{-1} P(a \leftrightarrow \gamma)^{1/2}$$

$\Delta\theta$ [mrad]	m_a [eV]	$g_{a\gamma\gamma}$ [Gev^{-1}]
0.0	$<$ 44	3.91×10^{-4}
1.0	3.4×10^{2}	3.10×10^{-4}
1.8	4.6×10^{2}	3.87×10^{-4}
10.0	1.1×10^{3}	3.69×10^{-4}
50.0	2.4×10^{2}	2.76×10^{-4}

T. Junk *"Confidence level computation for combining searches with small statistics"* Nucl. Instrum. Meth. A **434,** 435 (1999)

An X-ray Free Electron Laser (XFEL) is a light source, based on an electron LINAC

- LINAC accelerates electrons to $\sim 10\ \mathrm{GeV}$
- Undulators (periodic dipole magnets) cause beam to oscillate → radiation emitted
- **SASE** (Self Amplified Spontaneous Emission):
    - Emitted radiation interacts with beam causing microbunching
    - Microbunching amplifies light (coherent emission)
    - Very short pulse-duration (~ 10 fs)
- **Self-seeding –** monochromator in beamline imposes preferred length scale for microbunches → monochromatic light
- Extremely high "brilliance"
  $(N_\gamma /\ \mathrm{s}\ /\mathrm{mm}^2/\ \mathrm{mrad}^2/\ 0.1\%\mathrm{BW})$
- High impact science from drug discovery to fundamental physics with access decided in extremely competitive calls



Facility	Beam energy [GeV]	Photon energy [eV]	Pulse duration [fs]
EuXFEL	8.5 – 17.5	240 – 25,000	3-150
LCLS-II	4 – 15	200 – 25,000	1 – 500
SACLA	5.1 – 8.9	400 – 12,800	2 – 10

N. Huang *et al.* *"Features and futures of X-ray free-electron lasers"*. The Innovation. **2**, 2 (2021)